भारतीय मानक
Indian Standard

IS 16586 : 2016
(Reaffirmed 2021)

चुम्बकीय सामग्रियाँ सिंगल शीट टेस्टर के माध्यम से लौहा आधारित अमोर्फोंस स्ट्रप की चुंबकीय गुणधर्मों को मापने की पद्धतियाँ

Magnetic Materials — Methods of Measurement of the Magnetic Properties of Fe-Based Amorphous Strip by Means of a Single Sheet Tester

ICS 77.140.40

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Wrought Steel Products Sectional Committee, MTD 4

FOREWORD

This Indian Standard was adopted by the Bureau of Indian Standards, after the draft finalized by the Wrought Steel Products Sectional Committee and has been approved by Metallurgical Division Council.

After appropriate heat treatment, the strip exhibits quite a lower value of specific total loss in comparison to grain-oriented electrical steel strip. It is associated with low hysteresis loss due to low magnetic anisotropy and low eddy current loss due to a high resistivity and a thin thickness. However, it may deteriorate significantly by applying stress on the strip due to high magnetostriction and low magnetic anisotropy of the material.

The strip is usually supplied without any insulating coating. Consequently, an effect of inter-laminar eddy-current loss may increase the specific total loss values when the strip is laminated tightly into toroidal cores. Moreover, even if construction stresses induced by bending the strip into toroidal core could be removed by heat treatments, a small change in the diameter of test specimen cases unexpected stress in the material and then deteriorated magnetic properties may be obtained.

Therefore, methods of measurement of the magnetic properties of Fe-based amorphous strip by means of a single sheet tester are required.

Several attentions are necessary for the single sheet tester. Insignificant stress applied on the material could cause deterioration of magnetic properties of the material. Effects of the flux closure yoke, an introducing on stress into the material by a weight of upper yoke could be severe for the material. Therefore, a vertical single yoke is suitable to prevent the effects caused by an upper yoke. Moreover, deformation of the test specimen near the pole faces may introduce stress into the material. The H coil method is essential to avoid detecting the deteriorated properties of the test specimen beneath the pole faces. The material has lower magnetic anisotropy due to lack of crystalline anisotropy and its permeability is quite high, so the single sheet tester is recommended to be equipped a magnetic shield to prevent unexpected magnetization by the geomagnetic field.

Thin thickness, higher permeability and low total loss of the Fe-based amorphous strip bring weak output signals from the secondary coil, the H coil and the shunt resister to measure the magnetizing current of the SST apparatus. These signals shall be amplitude using low noise pre-amplifiers before the data acquisition devices. The digital sampling method is recommended to measure these weak signals. Observations of hysteresis loops are necessary to check the quality of measurements.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 1960 ‘Rules for rounding off numerical values (*revised*)’. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

Indian Standard

MAGNETIC MATERIALS — METHODS OF MEASUREMENT OF THE MAGNETIC PROPERTIES OF Fe-BASED AMORPHOUS STRIP BY MEANS OF A SINGLE SHEET TESTER

1 SCOPE

This standard specifies methods for the measurement of a.c. magnetic properties of Fe-based amorphous strips at frequencies up to 400 Hz.

The object of this part is to define the general principles and the technical details of the measurement of the magnetic properties of Fe-based amorphous strips by means of a single sheet tester.

The single sheet tester is applicable to test specimens obtained from Fe-based amorphous strips of any quality. The a.c. magnetic characteristics are determined for a sinusoidal induced voltage, for specified peak values of magnetic polarization and for a specified frequency.

The measurements are made at an ambient temperature of 27 ± 5°C on test specimens which have first been demagnetized.

NOTES

1 Fe-based amorphous strip is much thinner and its specific total loss is much lower than electrical steel strips. So specifications of the single sheet tester are different from those for electrical steel sheets in accordance with IEC 60404-3 (1).

2 This standard can cover other materials which have similar magnetic properties and physical characteristics as Fe-based amorphous materials, such as nano-crystalline soft magnetic materials.

3 Throughout this standard the term 'magnetic polarization' is used as described in IEC 60050-121. In some standards of the 60404 series, the term "magnetic flux density" is used.

2 REFERENCES

The following standards contain provisions which, through reference in this text, constitute provisions of this standard. At the time of publication, the editions indicated were valid. All standards are subject to revision and parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below:

IS No./International Standards	*Title*
1885 (various parts)	Electrotechnical vocabulary
13795 (Part 1) : 1993	Glossary of terms relating to special alloys: Part 1 Soft magnetic materials
16585 : 2016	Magnetic materials – Specification for individual materials – Fe-based amorphous strip delivered in the semi-processed state
IEC 60050-121: 1998	International Electrotechnical Vocabulary — Part 121: Electromagnetism.
IEC 60050-221: 1990	International Electrotechnical Vocabulary — Part 221: Magnetic materials and components.
IEC 60404-3(1): 1992	Magnetic materials — Part 3: Methods of measurement of the magnetic properties of magnetic sheet and strip by means of a single sheet tester

3 TERMS AND DEFINITIONS

For the purpose of this standard, the terms and definitions relating to magnetic properties given in IS 13795 (Part 1), IS 1885 (Various parts), IEC 60050-121 and IEC 60050-221 shall apply.

4 GENERAL PRINCIPLES

4.1 Principle of the Method

This method adopts the H coil method.

Any other International standards/methods are also applicable when the supplier and the purchaser agree.

The test specimen comprises a sample of Fe-based amorphous strip and is placed inside the following two windings:

a) An exterior primary winding (magnetizing winding); and
b) An interior secondary winding (voltage winding).

An H coil, that detects the strength of magnetic field where the test specimen is enclosed, is placed under surface of the test specimen.

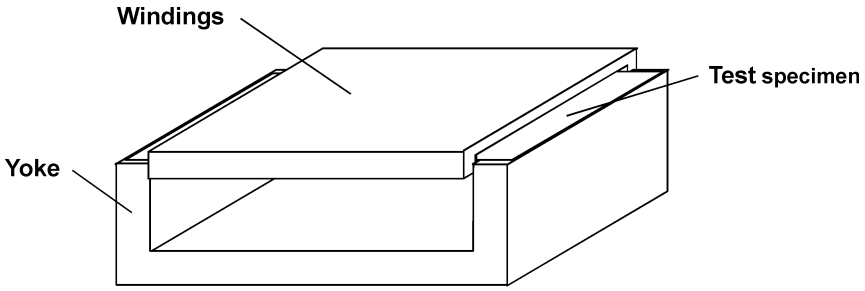


FIG. 1 DIAGRAM OF THE TEST APPARATUS

The flux closure is made by a magnetic circuit consisting of a single vertical yoke, the cross-section of which is very large compared with that of the test specimen (*see* Fig. 1).

The digital sampling method is recommended to measure the a.c. magnetic properties of the materials. The apparatus and the windings shall be connected as shown in Fig. 2.

The following signals should be measured as time functional data, which can represent waveform of magnetic flux, magnetic field strength and magnetizing current:

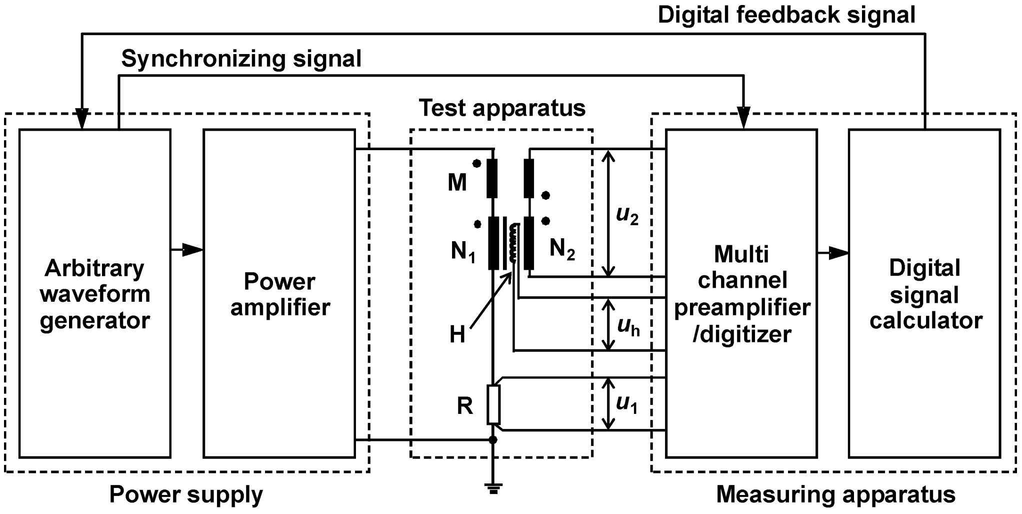
a) Voltage induced in the secondary winding;
b) Voltage induced in the H coil; and
c) Voltage across a non-inductive precision resistor in series with the primary winding.

NOTES

1 Because of smaller cross-section of the test specimen, lower loss properties and higher permeability of the Fe-base amorphous strip than electrical steel sheets, the power loss in yoke cannot be neglected in comparison to the loss in the test specimen. Therefore the magnetizing current method, which adopted in the single sheet tester for electrical steel sheets in accordance with IEC 60404-3(1), results much higher values of the specific total loss than those of the H coil method.

2 The magnetizing current method based on the wattmeter method that measured total power consumed in the magnetic circuit as vector products of the magnetizing current and the secondary voltage, would be disadvantageous because the influence of the yokes is the more significant due to the thinner and magnetically softer sample.

3 Addition of an upper yoke can effect to deteriorate the magnetic properties of Fe-based amorphous strip. The upper yoke apply pressure on the test specimen, and as a result, stresses are introduced in the material. Moreover, large magnetostriction of Fe-based amorphous material causes compressive stress in the material if both end of the test specimen was clamped by the pole faces of the yokes. These effects are considered larger



Key Components

M — mutual inductor for air flux compensation
N_2 — secondary winding
R — non-inductive precision resistor
u_h — voltage induced in H coil
N_1 — primary winding
H — H coil
u_2 — voltage induced in secondary winding
u_1 — voltage drop across the non-inductive precision resistor R_n

FIG. 2 CIRCUIT FOR THE DIGITAL SAMPLING METHOD

than loss increase by planer eddy currents in the test specimen on the pole faces of the lower yoke.

4 The voltage induced in the H coil is weak and have not enough signal-to-noise quality to input a wattmeter directly. So, it is difficult to measure the specific total loss of the test specimen using the A-V-W meter method with sufficient reproducibility required in this standard. The digital sampling method can overcome the difficulties and is now common to the measurement of magnetic properties.

4.2 Test Specimen

The test specimen shall be sampled in accordance with the product standard IS 16585.

The length of the test specimen shall be no less than 280 mm that is outside dimension of the distance over the pole faces of the yokes. Although the part of the specimen situated outside the pole faces has no great influence on the measurement, this part shall not be longer than is necessary to facilitate insertion and removal of the test specimen.

The test specimen shall be with as-cast edge and cut in length from Fe-based amorphous strip without the formation of excessive burrs or mechanical distortion. The test specimen shall be plane and rectangular.

The test specimen shall be heat treated in a d.c. magnetic field directed parallel to the casting direction according to the instructions of the manufacturer. The test specimen shall be flat during the heat treatment.

Care shall be taken in handling of the test specimen after the heat treatment to avoid rising fragments of the strip or creating mechanical stresses in the test specimen, because Fe-based amorphous strip is usually brittle after the heat treatment.

When supplier and purchaser agree to apply any other International standards/methods, the length, width of the test specimen and the number of stacks and specimens shall be determined by agreement between parties when ordering.

NOTE — Nominal widths of Fe-based amorphous strip are 142.2 mm, 170.2 mm and 213.4 mm.

4.3 Test Apparatus

4.3.1 *General*

The test apparatus comprises windings and yokes (*see* Fig. 1).

A mutual inductor for air flux compensation and a non-inductive precision resistor for current measurement are included with the single sheet tester (*see* Fig. 2).

Care shall be taken to ensure that temperature changes are kept below a level likely to produce stress in the test specimen due to thermal expansion or contraction.

4.3.2 *Yoke*

The yoke is in the form of a letter U made up of soft ferrite. It shall have a low residual magnetization, a low reluctance and a low specific total loss.

The yoke shall have pole faces having a width of 20 ± 1 mm. The two pole faces of each yoke shall be as flat as possible and coplanar to within 0.1 mm. Also, the yoke shall be rigid in order to avoid creating mechanical stresses in the test specimen.

The height of each yoke shall be between 80 mm and 120 mm. Each yoke shall have a width of 220 ± 1 mm and an inside length of 240 ± 1 mm (*see* Fig. 3).

When the supplier and the purchaser agree to apply any other International standards/methods, other yoke dimensions can be used by agreement between parties when ordering.

There shall be a specimen support, which made of non-conductive and non-magnetic materials, between the vertical limbs of the yokes. This surface support, on which the test specimen is supported, shall be in the same plane with the pole faces so that the test specimen can contact the pole faces with minimum air gaps.

NOTES

1 Higher residual magnetization of yokes cause higher d.c. bias of magnetization of the test specimen.

2 The yoke can be made of insulated sheets of grain oriented electrical steel or nickel iron alloy instead of soft ferrites provided that the compatibility of the results can be demonstrated.

3 Values of magnetizing current measured by the single sheet tester include effects of reluctances of yokes, conventional magnetic path length and air gaps between the pole faces of yokes and the test specimen. Therefore, the magnetic field strength and the specific apparent power calculated by the values of magnetizing current with the conventional magnetic path length are fairly larger than the value measured by the H coil method.

4 Other yoke dimensions can be used provided that the comparability of the results can be demonstrated.

5 In the case that the magnetizing current method is adopted, values of total loss are measured including power losses in yokes. The power loss in the yoke at magnetic flux of each measurement conditions can be measured by making a magnetic closure circuit using an upper yoke that is the same with the lower yoke, and using primary and secondary windings wound on the yokes. 25 turns are sufficient for each of these windings.

6 If there are steps between the surface of the test support plane and the pole faces, deteriorated magnetic properties are measured.

4.3.3 *Windings*

The primary winding shall be at least 230 mm in length. The secondary winding shall be between 100 mm and 120 mm in length and centred in the primary winding. The primary and secondary windings shall be wound on a non-conducting, non-magnetic, rectangular former.

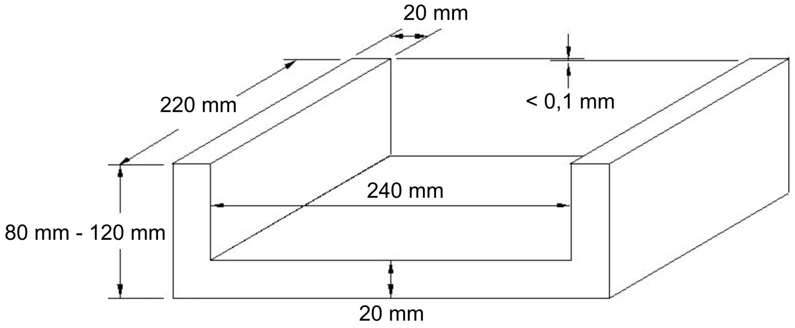


FIG. 3 YOKE DIMENSIONS

The dimensions of the former shall be as follows:

a) Length for winding — 235 mm ± 5 mm
b) Internal width — 220 mm +3 mm and no negative tolerance
c) Internal height — 3 mm ± 1 mm
d) External height — ≤ 12 mm

The primary winding can be made up of a single continuous and uniform winding taking up the whole length. One example of the winding can be made up of 220 turns of copper wire 1 mm in diameter taking up the whole length, wound in one or more layers.

The number of turns on the secondary winding depends on the characteristics of the measuring instruments.

The H coil shall be the same length with the secondary winding and centred in the primary winding. The H coil shall be wound on a non-conducting, non-magnetic and rectangular plate. The width of the plate shall be 100 mm to 120 mm and the height of the plate shall be not larger than 3 mm.

The H coil shall be embedded in the specimen support plate and the distance between the surface of the support plate and the surface of the H coil shall be as small as possible, not larger than 1 mm.

When the supplier and the purchaser agree to apply any other International standards/methods, windings and the dimensions of the former shall be determined by agreement between parties when ordering.

4.3.4 *Air Flux Compensation*

Compensation shall be made for the effect of air flux on the secondary voltage at measurements of the peak values of magnetic polarization for set values of the peak values of magnetic field strength. This air flux compensation is not necessary at measurements of the specific total losses because the effect is negligible at low magnetic field strength.

This can be achieved, for example, by a mutual inductor. The primary winding of the mutual inductor is connected in series with the primary winding of the test apparatus, while the secondary winding of the mutual inductor is connected to the secondary winding of the test apparatus in series opposition (*see* Fig. 2).

The adjustment of the value of the mutual inductance shall be made so that, when passing an alternating current, corresponding to the maximum magnetic polarization for such as 80 A/m, through the primary windings in the absence of the specimen in the test apparatus, the voltage measured between the non-common terminals of the secondary windings shall be no more than 0.1 percent of the voltage appearing across the secondary winding of the test apparatus alone.

Thus the average value of the rectified voltage induced in the combined secondary windings is proportional to the peak value of the magnetic polarization in the test specimen.

Air flux compensation can be achieved, for example, by the numerical air flux compensation or by subtractions of the averaged rectified values of secondary voltage measured for the same peak value of magnetic field strength in the absence of the test specimen from the averaged rectified values of secondary voltage at the measurements.

4.3.5 *Non-Inductive Precision Resistor*

A non-inductive precision resistor of an accuracy of ± 0.1 percent or better shall be used to measure the magnetizing current. In order to minimize the distortion of the magnetic polarization waveform, the resistance value shall be as small as possible depending upon the characteristics of the measuring instruments; the recommended resistance value is to below 1 Ohm (Ω).

A four-terminal resistor of sufficient heat capacity is recommended and then the two current terminals shall be connected in series with the primary winding and two potential terminals shall be connected to an input channel of the measuring instrument (*see* Fig. 2).

4.3.6 *Magnetic Shield*

Fe-based amorphous material is nearly isotropic and its permeability is quite high, so the single sheet tester is recommended to be equipped a magnetic shield to prevent unexpected magnetization by the geomagnetic field,

NOTE — Even, if the magnetic axis of the test apparatus settled at right angle the direction of geomagnetism, the geomagnetic field can magnetize the test specimen in a substantial degree at cross direction of the a.c. magnetization.

4.4 Power Supply

4.4.1 *General*

The power supply shall consist of an arbitrary waveform generator and a power amplifier, or an instrument integrating both these functions (*see* Fig. 2).

In addition, the waveform of the secondary voltage shall be maintained as sinusoidal as possible. It is preferable not only to maintain the form factor of the secondary voltage to within ± 1 percent of 1.111 but also to suppress harmonic contents in the secondary voltage as small as possible. This can be achieved by various means, for example by using digital means described in Annex A.

NOTE — The form factor of the waveform is the ratio of the r.m.s. value to the average rectified value.

4.4.2 *Arbitrary Waveform Generator*

The arbitrary waveform generator shall synthesize a signal of magnetizing waveform, amplitude and frequency data which are programmed externally, and shall convert the signal to voltage using a digital-to-analogue (D/A) convertor consecutively in coincidence with a readout clock to synchronize with the sampling clock of analogue-to-digital (A/D) convertors of the measuring apparatus (*see* Fig. 2).

The D/A convertor shall have a sufficiently high resolution and the number of signal data in one magnetizing period should be sufficiently large. A low pass filter should be inserted between the arbitrary waveform generator and the power amplifier to reduce higher harmonics that can cause aliasing at digitising of measuring apparatus.

In order to synchronize the arbitrary waveform generator and the digitizer, a common clock shall be used to synchronize the readout clock of the generator with the sampling clock of the digitizer. An arbitrary waveform generator with two-channel outputs using a common readout clock may be used; one output generates the magnetization signal to the power amplifier and the other output synchronizes the sampling clock of the digitizer (*see* Fig. 2).

4.4.3 *Power Amplifier*

The power amplifier shall be of low internal impedance and shall be highly stable in terms of voltage and frequency, being sufficiently low noise on the voltage. During the measurement, the voltage and frequency shall be maintained constant within ± 0.2 percent.

The power amplifier should be a bipolar type with low noise and wide ranges of frequency and voltage.

NOTE — The output of the bipolar power amplifier can handle source and sink current as well as positive and negative voltage. It is suitable for an inductive load of low impedance.

4.5 Measuring Apparatus

4.5.1 *General*

The measuring apparatus shall consist of a digitizer with at least three A/D convertors and a digital signal calculator, or an instrument integrating both these functions (*see* Fig. 2).

In order to transform digital data, the digitizer shall be connected to the digital signal calculator by a data bus (*see* Fig. 2).

4.5.2 *Digitizer*

The digitizer shall be comprised of at least three independent signal channels of calibrated pre-amplifiers, sample-and-hold circuits (S/H) and calibrated A/D converters. The S/H shall work simultaneously with a sampling clock synchronized with the readout clock of the arbitrary waveform generator (*see* Fig. 2).

NOTE — The digitizer can be a digital storage oscilloscope with required function.

The single channels shall have sufficiently high input impedance and low input capacitance typically 1MΩ (Megaohm) in parallel with about 100 pF (picofarad) to avoid loading of the secondary winding.

The phase shift difference among the channels shall be sufficiently small even at the lowest power factor.

The A/D convertor shall have a sufficiently high resolution to reduce the digitizing error. 12-bit or larger resolution is recommended.

The sampling clock shall be at a sufficiently high rate. The rate of samplings per one magnetization period is recommended not less than 512.

The synchronous averaging of the signal over the several periods is effective to remove noise on the signal.

NOTE — It is also convenient if the sampling number shall be equal to the power of 2 in terms of digital data processing such as the fast Fourier transform (FFT).

4.5.3 *Digital Signal Calculator*

The numerical data set of signals shall be transferred from the digitizer to the digital signal calculator and the magnetic properties shall be determined using the dataset.

In order to maintain the waveform of the secondary voltage by using digital means described in Annex A, the digital signal calculator calculates the magnetizing waveform and its amplitude that can achieve the prescribed sinusoidal waveform and peak value of the secondary voltage and carries out the digital feedback signal to the signal generator (*see* Fig. 2).

NOTE — The digital signal calculator can be a personal computer (PC) or a digital signal processor (DSP) that is composed of a sufficiently fast digital multiplier and adder.

5 MEASUREMENT PROCEDURE

5.1 Principle of Measurement

The specific total loss of the test specimen is determined by calculating the area of the hysteresis loop composed of time-function waveform of the magnetic field strength, $H(t)$ and the magnetic polarization, $J(t)$.

The data pair of signals, $U_H(t)$ digitized from the voltage in the H coil and $U_2(t)$ digitized from the voltage of the secondary coil represent the magnetic field strength, $H(t)$, and the time derivative of magnetic polarization, $dJ(t)/dt$, respectively; both are functions of time, t. The date pairs sampled over one period of magnetization provide the complete information for one measurement.

This data set enables to determine all magnetic properties required in this standard.

5.2 Preparation of Measurement

The length of the test specimen shall be measured with an accuracy of ± 0.1 percent and its mass determined within ± 0.1 percent. The test specimen shall be loaded and centred on the longitudinal and transverse axes of the windings.

The cross-sectional area, A , of the test specimen shall be calculated using the following formula:

$$A = \frac{m}{l\rho_m} \qquad \ldots(1)$$

A = cross-section area of the test specimen, expressed, in square metre (m^2);

m = mass of the test specimen, expressed, in kilogram (kg);

l = length of the test specimen, expressed, in metre (m); and

ρ_m = density of the test material, expressed, in kilogram per cubic metre (kg/m^3).

Before measurement, the test specimen shall be demagnetized from well above the value of magnetic field strength to be measured at by slowly decreasing the corresponding magnitude of the magnetizing current to zero.

5.3 Adjustment of Power Supply

In practice, single or groups of peak values of magnetic polarization, $\hat{J}$, and magnetic field strength, $\hat{H}$, are set at a specified frequency.

For the measurements of the specific total loss, the specific apparent power, r.m.s. value of magnetic field strength and the peak value of the magnetic field strength, $\hat{J}$ shall be set by adjusting power supply.

For the measurement of the peak value of magnetic polarization, $\hat{H}$ shall be set.

The output of the power supply shall be slowly increased until $\hat{J}$ or $\hat{H}$ has reached the desired value. The output of the power supply shall not decrease during the measurement.

The data set of $U_H\ (i)$ and $U_2\ (i)$ shall be measured over one or several periods of magnetization by the digitizer and calculated by the digital signal calculator.

The wave form of the secondary voltage, $dJ(t)/dt$, should be checked to ensure that only the fundamental component is present.

The shape of the hysteresis loop of $J(t)$ and $H(t)$ shall be checked to ensure that a symmetrical loop is presented.

6 DETERMINATION OF CHARACTERISTICS

6.1 General

All the required magnetic properties shall be determined through numerical calculations using the data set of $U_H\ (i)$ and $U_2\ (i)$.

6.2 Determination of the Magnetic Polarization

The magnetic polarization at the time t, $J(t)$, shall be calculated from the following equation:

$$J(t) = -\frac{1}{N_2 A \alpha_B} \int_0^t U_2(t) dt + K \qquad \ldots(2)$$

where

$J(t)$ = magnetic polarization at a time t, in tesla (T);

N_2 = number of turns of the secondary winding;

A = cross-sectional area of the test specimen, in square metre (m^2);

α_n = combined amplitude of the instruments in the secondary circuit;

$U_2(t)$ = secondary voltage at a time t, in volt (V); and

K = constant such that the time average of $B(t)$ is zero.

6.3 Determination of the Magnetic Field Strength

The magnetic field strength at the time t, $H(t)$ shall be calculated from the following equation:

$$H(t) = -\frac{1}{\mu_0 \left(N_H A_H\right) \alpha_H} \int_0^t U_H(t)\mathrm{d}t + \Lambda \qquad \ldots(3)$$

where

$H(t)$ = magnetic field strength at a time t, in ampere per metre (A/m);

$(N_H A_H)$ = area-turns of the H coil, expressed, in square metre (m^2);

α_H = combined amplitude of the instruments in the H coil circuit;

$U_H(t)$ = secondary voltage at a time t, in volt (V); and

Λ = constant such that the time average of $H(t)$ is zero.

The area-turns of H coil can be determined in a uniform field using a solenoid coil of enough diameters and length to obtain uniform field over the volume of the H coil before installing the H coil into the former. After the H coil was installed in the former, the area-turns of H coil may be determined in comparison of the peak values of magnetic field strength obtained by the H coil method and the magnetizing current method or a separated H coil, placed in the centre of the windings, which should be calibrated before in a uniform field. The peak value of magnetic field strength by the magnetizing method is calculated by the following equation:

$$\hat{H} = \frac{N_1}{l_m R}\hat{U}_1 \qquad \ldots(4)$$

where

$\hat{H}$ = peak value of magnetic field strength, $H(t)$, in ampere per metre (A/m);

N_1 = number of turns of the primary winding;

l_m = conventional effective magnetic path length, in metre (m); $l_m = 0.24$ m;

R = value of the resistance of the non-inductive precision resistor in series with the primary winding to determine the magnetizing current, in ohm (Ω);

$\hat{U}_1$ = peak value of voltage, $U_1(t)$, developed across the non-inductive precision resistor R in series with the magnetizing winding, in volt (V).

6.4 Determination of the Specific Total Loss

The specific total loss, P_s, corresponds to the area of the hysteresis loop composed of $J(t)$ and $H(t)$.

Thus, the specific total loss P_s of the test specimen shall be calculated in accordance with the following equation:

$$P_s = \frac{f}{\rho_m}\int_{t=0}^{T} H(t)\frac{\mathrm{d}J(t)}{\mathrm{d}t}\mathrm{d}t = \frac{f}{\rho_m N_2 A}\int_{t=0}^{T} H(t)U_2(t)\mathrm{d}t \qquad \ldots(5)$$

where

P_s = specific total loss of the test specimen, in watt per kilogram (W/kg);

ρ_m = conventional density of the test material, in kilograms per cubic metre (kg/m^3);

f = frequency, in hertz (Hz);

T = period where $T = 1/f$, in second (s);

N_2 = number of turns of the secondary winding;

A = cross-sectional area of the test specimen, in square metre (m^2);

$H(t)$ = magnetic field strength at time t, in ampere per metre (A/m);

$J(t)$ = magnetic polarization at a time t, in tesla (T); and

$U_2(t)$ = secondary voltage at time t, in volt (V).

6.5 Determination of the Specific Apparent Power

The specific apparent power, S_s, of the test specimen corresponds to the product of the r.m.s. value of the magnetic field strength and the r.m.s. value of magnetic polarization.

The specific apparent power S_s shall be calculated as follows:

$$S_s = \frac{1}{\rho_m}\tilde{H} \cdot \tilde{J} \qquad \ldots(6)$$

where

S_s = specific apparent power of the test specimen, expressed, in volt ampers per kilogram (VA/kg);

ρ_m = conventional density of the test material, in kilogram per cubic metres (kg/m^3);

$\tilde{H}$ = r.m.s. value of magnetic field strength, $H(t)$, in ampere per metre (A/m); and

$\tilde{J}$ = r.m.s. value of magnetic polarization, $J(t)$, in tesla (T).

7 REPRODUCIBILITY

The reproducibility of the results obtained from the procedures described in this clause depends essentially upon the accuracy of the instruments used for the measurement and careful attention to the physical details of the test equipment.

The reproducibility of the specified total loss measurement is characterized by a relative standard deviation of 2 percent for measurement on Fe-based amorphous strip at magnetic polarization up to 1.3 T. For measurements at higher magnetic polarizations, it is expected that the relative standard deviation will be increased.

The reproducibility of the peak value of magnetic polarization measurement is characterized by a standard deviation of the order of 1 percent.

The reproducibility of the specific apparent power measurement is characterized by a standard deviation of 6 percent.

ANNEX A

(*Clause* 4.4.1)

SINUSOIDAL WAVEFORM CONTROL BY DIGITAL MEANS

A-1 GENERAL

For the determination of the specific total loss and the specific apparent power, the waveform of the magnetic polarization should be generally maintained sinusoidal with a form factor of 1.111 ± 1 percent. The form factor of the waveform is the ratio of the r.m.s. value to the average rectified value.

The prescribed sinusoidal waveform, frequency and amplitude of the magnetic polarization may be difficult to achieve by means of conventional analogue feedback techniques at higher magnetic polarizations. Instabilities and auto-oscillations are, in fact, likely to occur when the magnetic polarization is increased. The digital feedback method [5, 6] is expected to be immune from auto-oscillatory effects.

In a possible realization of this method, it is assumed that the time functions $J(t)$ and $H(t)$ form a parametric representation of the hysteresis loop $J(H)$. Under this assumption, a certain time dependence of the current in the primary circuit [that is $H(t)$] automatically defines the $J(t)$ function.

An arbitrary signal generator controlled by computer is employed to provide the required $H(t)$ function. An iterative procedure is devised, where at each ith step the dynamic $J(H)$ relationship is refreshed by the actual $J_i(t)$ and $H_i(t)$ functions and is used to calculate the function $H_{i+1}(t)$ at the $(i+1)$ th step. The iteration can be stopped once the prescribed form factor value of the magnetic polarization is attained.

The so-calculated $H_{i+1}(t)$ function should be translated into a voltage function $U_{i+1}(t)$, to be fed into the arbitrary signal generator at $(i+1)$th step. $U_{i+1}(t)$ can be calculated from the following equation, neglecting spurious capacitance effects:

$$U_{i+1}(t) = \frac{N_1}{GN_2}\left[U_J(t) + U_{air}(t) + U_{RI}(t)\right] \qquad \ldots(7)$$

$$U_J(t) = N_2 A \frac{dJ_{set}(t)}{dt} \qquad \ldots(8)$$

$$U_{air}(t) = \mu_0 N_2 A_1 \frac{dH_{i+1}(t)}{Dt} \qquad \ldots(9)$$

$$U_{RI}(t) = R_S I_1 \qquad \ldots(10)$$

where

$U_{i+1}(t)$ = voltage to be fed into the arbitrary signal generator at $(i+1)$th step, a time function, expressed in volt (V);

N_1 = total number of turns of the primary winding;

G = gain of the power amplifier;

N_2 = total number of turns of the secondary winding;

$U_J(t)$ = induced voltage of the magnetic polarization of the test specimen in the secondary winding, a time function, expressed in volt (V);

$U_{air}(t)$ = additional inductive voltage developed by the effect of air flux across the magnetizing winding, a time function, expressed in volt (V);

$U_{RI}(t)$ = resistive voltage developed in the magnetizing circuit, a time function, expressed, in volt (V);

G = cross-sectional area of the test specimen, expressed, in square metre (m^2);

$J_{set}(t)$ = set sinusoidal signal of the magnetic polarization, a time function, expressed in tesla (T);

$H_i(t)$ = magnetic field strength at i-th step, a time function, expressed, in ampere per metre (A/m);

A_1 = effective cross-sectional area of the magnetizing winding, expressed, in square metres (m)

μ_0 = magnetic constant; $4\pi \times 10^{-7}$ henrys per metre (H/m);

π = number 3.141 592 6... ;

R_s = total series resistance of the primary circuit, expressed in ohms (Ω); and

I_1 = primary current, expressed in amperes (A).

An alternative method of signal control is possible. A voltage $U_{i+1}(t)$, to be fed into the arbitrary signal generator at (i+1) th step, can be calculated from equation (11) instead of equation (7). In this case, the voltage $U_{i+1}(t)$ is calculated from the difference between the measured voltage induced in the second winding $U_2(t)$ and the target voltage induced in the second winding for the desired set point $U_J(t)$ without setting a field strength function.

$$U_{i+1}(t) = U_i(t) + \mathrm{K}\frac{N_1}{GN_2}[U_J(t) - U_2(t)] \qquad \ldots(11)$$

where

$U_{i+1}(t)$ = voltage to be fed into the arbitrary signal generator at (i+1)th step, a time function, expressed, in volt (V);

$U_J(t)$ = calculated voltage induced across the secondary winding when the set magnetic polarization has been achieved, a time function, expressed, in volt (V);

$U_2(t)$ = voltage induced in the secondary winding, a time function, expressed, in volt (V);

K = constant of negative-feedback; positive value below 1.0; and

G = gain of the power amplifier.

Because the signal control by digital means is the repetition of magnetization, acquisition of the signals, demagnetization, and waveform deformation, the total time for signal control becomes longer compared with the analogue case. In order to reduce the total control time, the special arbitrary signal generator can be switched synchronously between the two independent waveforms.

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